2. Summary of the Transactional Interpretation

Albert Einstein distrusted quantum mechanics (QM) in part because he perceived in its formalism what he called ‘‘spooky actions at a distance’’[2]. The action-at-a-distance characteristic that worried Einstein is now called *nonlocality*. It is generally acknowledged to be inextricably embedded in the quantum mechanics formalism. Let us then define our terms. *Locality* means that isolated parts of any quantum mechanical system out of speed-of-light contact with other parts of that system are allowed to retain definite relationships or correlations only through memory of previous contact. *Nonlocality* means that in quantum mechanical systems relationships or correlations not possible through simple memory are somehow being enforced faster-than-light across space and time. Close examination of the correlations present in recent experimental tests of Bell’s inequality provide concrete examples of such nonlocality.

At the interpretational level, the nonlocality of the quantum mechanics formalism is a source of some difficulty for the Copenhagen interpretation. It is accommodated in the CI through Heisenberg’s ‘‘knowledge interpretation’’ of the quantum mechanical state vector as a mathematical description of the state of observer knowledge rather than as a description of the objective state of the physical system observed. For example, Heisenberg in a 1960 letter to Renninger wrote[3], ‘‘The act of recording, on the other hand, which leads to the reduction of the state, is not a physical, but rather, so to say, a mathematical process. With the sudden change of our knowledge also the mathematical presentation of our knowledge undergoes of course a sudden change.’’ The knowledge interpretation’s account of state vector collapse and nonlocality is internally consistent but is regarded by some (including the author) as subjective and intellectually unappealing. It is the source of much of the recent dissatisfaction with the Copenhagen interpretation.

The author has proposed an alternative and more objective interpretation of the quantum mechanics formalism called the *transactional interpretation* (TI). It employs an explicitly nonlocal ‘‘transaction’’ model for quantum events. This model describes any quantum event as a ‘‘handshake’’ executed through an exchange of advanced and retarded waves and is based on time symmetric Lorentz-Dirac electrodynamics and on ‘‘absorber theory’’ originated by Wheeler and Feynman. In the absorber theory description any emission process makes advanced waves (schematically represented by the time dependence $e^{+i\omega t}$) on an equal basis with ordinary ‘‘retarded’’ waves ($e^{-i\omega t}$). Both advanced and retarded waves are valid orthogonal solutions of the electromagnetic wave equation, but in conventional electrodynamics the advanced solutions are conventionally rejected as unphysical or acausal. Wheeler and Feynman used a more subtle boundary condition mechanism to eliminate the non-causal effects of the advanced solutions.

In the Wheeler-Feynman picture when the retarded wave is absorbed at some time in the future, a process is initiated by which canceling advanced waves from the absorbers erase all traces of advanced waves and their ‘‘advanced’’ effects, thereby preserving causality. An observer not privy to these inner mechanisms of nature would perceive only that a retarded wave had gone from the emitter to the absorber. The absorber theory description, unconventional though it is, leads to exactly the same observations as conventional electrodynamics. But it differs in that there has been a two-way exchange, a ‘‘handshake’’ across space-time which led to the transfer of energy from emitter to absorber.

This advanced-retarded handshake is the basis for the transactional interpretation of quantum mechanics. It is a two-way contract between the future and the past for the purpose of transferring energy, momentum, etc, while observing all of the conservation laws and quantization conditions imposed at the emitter/absorber terminating ‘‘boundaries’’ of the transaction. The transaction is explicitly nonlocal because the future is, in a limited way, affecting the past (at the level of enforcing correlations). It also alters the way in which we must look at physical phenomena. When we stand in the dark and look at a star a hundred light years away, not only have the retarded light waves from the star been traveling for a hundred years to reach our eyes, but the advanced waves generated by absorption processes within our eyes have reached a hundred years into the past, completing the transaction that permitted the star to shine in our direction.

It is a serious interpretational problem for the Copenhagen interpretation that it characterizes as mathematical descriptions of the knowledge of observers the solutions of a simple second-order differential equation relating momentum, mass, and energy. Similarly, it is a problem for the transactional interpretation that it uses advanced solutions of wave equations for retroactive confirmation of quantum event transactions. While this provides the mechanism for its explicit nonlocality, the use of advanced solutions seems counterintuitive and contrary to common sense, if not to causality. Can this account of a quantum event be truly compatible with the austere formalism of quantum mechanics?

From one perspective the advanced-retarded wave combinations used in the transactional description of quantum behavior are quite apparent in the Schrödinger-Dirac formalism itself, so much so as to be almost painfully obvious. Wigner’s time reversal operator is, after all, just the operation of complex conjugation, and the complex conjugate of a retarded wave is an advanced wave. What else, one might legitimately ask, could the ubiquitous ψ^* notations of the quantum wave mechanics formalism possibly denote except that the time reversed (or advanced) counterparts of normal (or retarded) ψ wave functions are playing an important role in a quantum event? What could an overlap integral combining ψ with ψ^* represent other than the probability of a transaction through an exchange of advanced and retarded waves? At minimum it should be clear that the the transactional interpretation is not a clumsy appendage gratuitously grafted onto the formalism of quantum mechanics but rather a description which, after one learns the key to the language, is found to be graphically represented within the quantum wave mechanics formalism itself.

The latter half of my review article[1] provides examples of the use of the transactional interpretation in analyzing the accumulated curiosities and paradoxes (the EPR paradox, Schrödinger’s cat, Wigner’s friend, Wheeler’s delayed choice, Herbert’s paradox, etc.) that have lain for decades in the quantum mechanics Museum of Mysteries. It is shown that the TI removes the need for half-and-half cats, frizzy universes with split ends, observer-dependent reality, and ‘‘knowledge’’ waves. It removes the observer from the formalism and puts him back in the laboratory where he belongs.

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3. Differences between the Transactional and the Copenhagen Interpretations

In this section I want to focus on the differences between the transactional interpretation and the Copenhagen interpretation. I have decided to do this with a question and answer format, asking an interpretational question implicit in the quantum mechanics formalism and then providing answers from the points of view of both the Copenhagen interpretation (CI) and the transactional interpretation (TI). The answers given are based on my understanding of both interpretations, and there is perhaps room for other views of how the CI might answer the questions posed. Where there was this sort of disagreement during the discussion session of this Conference, I will try to indicate this.

Q1: Does the wave described by the state vector have physical reality?

CI: The state vector does not describe a real physical wave moving through space, but rather a mathematical representation of the knowledge of an observer.

TI: To the extent that the formalism contains state vectors represented in position space (as opposed to momentum space or other parameter spaces), the formalism is describing real physical waves moving through space which are the first steps in the formation of transactions. The completed transaction describes the exchanged particle.

Discussion: It was pointed out in the Conference discussion that for some quantum mechanical systems (e.g. an ensemble of particles with spin) there is no known formalism capable of representing the system in position space. Therefore, it was argued, it is inappropriate to discuss ‘‘waves physically present in space’’. This is a very relevant observation, for the interpretation of a formalism cannot and should not go where the formalism itself does not venture. The TI, when applied to a formalism representing waves in position space, can interpret them as physically present in space. When applied to momentum space formalisms, etc, the issue of physical presence is moot, since it is not clear that ‘‘physical presence’’ in an arbitrary parameter space is a meaningful concept.

Q2: Are physical interactions involving observers different from other physical interactions?

CI: Yes. Physical interactions with an observer are qualitatively different from other physical interactions because they produce observer knowledge and cause state vector collapse.

TI: No. Physical interactions involving an observer are completely equivalent to any other physical interactions. A change in observer knowledge is a necessary consequence of state vector collapse, not a cause.

Discussion: In the Conference discussion Prof. von Weizsäcker disagreed with this dichotomy. His point was that there is no distinction made in the formalism between observer interactions and any other interactions. That is of course correct, but my point here is that there is a difference in these interactions at the interpretational level precisely because the Copenhagen interpretation treats observer interactions differently, (e.g, by using them to collapse the state vector), even though the QM formalism does not.

Q3: Can one ask interpretational questions about aspects of the formalism that are not observable?

CI: No. One should confine one’s attention to the observables and to statical predictions of their values; discussion of non-observables is meaningless.

TI: Yes. One can discuss most of non-observable constructs of the quantum mechanics formalism, and can even visualize nonlocal quantum processes.

Discussion: As discussed in my review article[1], the positivistic aspect of the Copenhagen interpretation can be considered detachable, but the discussions at this Conference indicate that it remains an important aspect of the CI, at least to some of the attendees.

Q4: Is the state vector unique in the sense that only one state vector is required to describe a given physical system?

CI: No. A separate state vector is required for each observer of a given physical system.

TI: Yes. A single state vector describes a physical system, no matter how may observers make measurements on it.

Discussion: It was demonstrated in my review article[1] that at the interpretational level a paradox arises if one assumes (1) the CI account of state vector collapse and (2) that a single state vector describes a system involving two separated measurement events not lying in the same light cone. The conclusion is that the only consistent use of the Copenhagen interpretation is to attribute separate state vectors to measurements which do not share the same light cone. This does not necessarily count against the Copenhagen interpretation, but it is a point which is not widely appreciated. The transactional interpretation, on the other hand, describes all quantum events in terms of a unique state vector, even when measurements are involved which do not share the same light cone.

Q5: Is the interpretation capable of extension to developing relativistic quantum mechanics or quantum gravity formalisms?

CI: It is not obvious that such an extension is possible for the CI. Time and space are treated non-relativistically, and definite simultaneity is implied by the knowledge interpretation.

TI: There are no apparent obstacles to such an extension. Time and space are treated relativistically, and Lorentz invariance is effectively built into the transactional interpretation.

Discussion: The Copenhagen interpretation was developed specifically for interpreting the non-relativistic Schrödinger formalism. The structure of Newtonian space-time is deeply embedded in its approach, perhaps inextricably so. Further, attempts to apply the CI to systems involving no observers, for example the quantum dynamics of Big Bang era or the state vector of the universe as a whole, would seem to be at odds with the knowledge interpretation's need for external observers to provide state vector collapse.

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4. Equivalence Mapping of Interpretations

In a very interesting contribution to this Conference, Prof. von Weizsäcker and Dr. Görnitz[4] have argued that to the extent that the Copenhagen interpretation, the transactional interpretation, and other interpretations are both self-consistent and also consistent with the quantum mechanics formalism, one can deduce a ''dictionary'' or set of interpretational transformations which can render one interpretation in the terms or ''language'' of another. This demonstrates a kind of equivalence principle for interpretations. I believe that their argument is correct and that there is this sort of relationship between the transactional and Copenhagen interpretations. The formalism itself clearly provides one such link between one interpretation and another, so it should not be a surprise that such a transformation or remapping can be made.

One should proceed carefully, however, in reading too much significance into this result. In particular, the transformation procedure described is quite capable of mapping the *effects* in one interpretation into *causes* in the other, and vice versa, thereby reversing a causal relationships. For example, suppose that we carefully measure as a function of time the coordinates of a child on a swing and the coordinates of the moon moving in its orbit. It is then possible to characterize the motions of the moon in terms of the position of the child. This ''mapping'', however, places the child in an inappropriate position of central importance, for it gives the impression that the child's motion is somehow the cause of the moon's motion.

It is my view that the Copenhagen interpretation of quantum mechanics makes just this kind of causal error in attributing to collapse of the state vector to a change in the knowledge of an observer. Certainly the observer's change in knowledge is in good sequential correspondence with the collapse of the state vector, but this does not establish that the one is the cause of the other. Like the child in the swing, the Copenhagen interpretation places the observer in an inappropriately central position. The Copenhagen interpretation is observer-centric in the same sense that Ptolemaic astronomy is geo-centric. That one can map the epicycles of Ptolemy into the orbits of Copernicus does not demonstrate that the two theories are interchangeable.

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5. Advanced Waves and the Appropriateness of Wave Equations

During the discussion session of this Conference the question was once again raised concerning the appropriateness of the transactional interpretation's use of advanced waves in the interpretation of quantum formalisms which do not have advanced solutions. This question was carefully addressed in my RMP article, but since the issue has been raised, let me address it here.

The wave equation which has been the focus of most of the discussion surrounding the interpretation of quantum mechanics is the Schrödinger equation:

$$-\frac{\hbar^2}{2m}\nabla^2\psi = i\hbar\frac{\partial\psi}{\partial t} \quad (1)$$

where **m** is the mass of the particle described by the equation. This equation is first order in the time variable and for this reason does *not* have advanced solutions. Therefore, if ψ=**F**(r,t) is a solution of the Schrödinger equation, then $\psi*$=**G**(r,t) is not a solution, nor is a linear combination of **F** and **G** as used in the transactional model.

We must bear in mind, however, that the Schrödinger equation is ultimately not physically correct because it is not relativistically invariant. It should properly be considered as the limiting case, in a restricted non-relativistic domain, of some more physically reasonable relativistically invariant wave equation, e.g., the Dirac equation or the Klein-Gordon equation. These relativistic equations, like the electromagnetic wave equation, have both advanced and retarded solutions.

Considering the Schrödinger equation as a limiting case, the apparent problem created by its lack of advanced solutions can be resolved. When a suitable relativistic wave equations is reduced to the Schrödinger equation by taking a non-relativistic limit[5], the reduction procedure leads to *two* distinct equations, the Schrödinger equation and another equation of the form:

$$-\frac{\hbar^2}{2m}\nabla^2\psi = -i\hbar\frac{\partial\psi}{\partial t} \quad (2)$$

which is the complex conjugate or time reverse of the Schrödinger equation. This equation has *only* advanced solutions. Equations (1) and (2) are equally valid non-relativistic reductions of relativistic dynamics, but equation (2) is usually dropped because it has negative energy eigenvalues. From this it should be clear that **F**(r,t) and **G**(r,t) (or ψ and $\psi*$) are equally valid solutions of the dynamics which underlies the Schrödinger equation. It is therefore valid to use advanced solutions in the transactional model in the non-relativistic limit as if they were solutions of the Schrödinger equation.

We can also look at the need for relativistic invariance in another way. The interpretational problem of nonlocality, as mentioned above, is essentially a relativistic problem. If the velocity of light were infinite the locality problem would not exist: there would be no difference between local and non-local descriptions. The Schrödinger equation can be considered as the limiting case of a relativistically invariant wave equation when the velocity of light goes to infinity. Therefore it is not particularly surprising that an explicitly non-local description such as the transactional model may have intrinsic inconsistencies with the Schrödinger equation and may require certain properties of relativistically invariant wave equations. This is a subtle link between relativity and quantum mechanics which has not, perhaps, been previously appreciated.

However, let it be clearly understood that the transactional interpretation of quantum mechanics is applicable only to quantum mechanical formalisms that either have advanced solutions or that are special cases or reductions of more general formalisms that have advanced solutions. It is my view that valid QM formalisms that do not satisfy this criterion are a null set, but this proposition has not been proved.

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6. Collapse and the Quantum Mechanics Formalism

The ''collapse'' or reduction of the state vector of a quantum system to a definite state as the result of a measurement was first perceived in the operational procedures of the quantum formalism by John von Neumann[6]. He observed that in orthodox quantum formalism one represents a post-measurement quantum system with a state vector that is qualitatively different from that used to represents the pre-measurement quantum system. In a very interesting contribution to this Conference, Prof. Ballentine[7] demonstrates that while collapse is implicit in the formalism, the *mechanism* of state vector collapse in an individual quantum event is not, strictly speaking, a part of the formalism. Either, he argues, the formalism of quantum mechanics must be considered applicable only to a statistically large number of similar quantum events, or else one must supply an additional process, an extension of the formalism of quantum mechanics, to provide the collapse mechanism for individual events. He gave an example of such a process which involved an ''extra'' stochastic field.

This discussion is relevant to the transactional interpretation because the TI might be viewed as supplying a mechanism for state vector collapse. That appears to contradict Ballentine's requirement of an additional mechanism. Actually, there is no such contradiction. The TI's nonlocal collapse mechanism is strictly at the interpretational level. It cannot supply mechanisms missing from the formalism. The problem that Ballentine poses, that of accommodating collapse for a single quantum event, is one that must be addressed by the formalism. The transactional interpretation would then have to be considered in the context of such a revised formalism to decide if a conflict exists.

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7. Experimental Tests and the Transactional Interpretation

My discussion of quantum mechanics interpretations[1] stressed the point that the interpretation of a mathematical formalism *cannot* be tested experimentally and must be judged on other grounds. In this section I would like to make a related point: while interpretations cannot be directly tested, it is possible for experimental results to favor one interpretation or another.

For example, suppose that a new physical phenomenon were discovered which, in its physical interactions, was qualitatively different in its effects when observed by a conscious and intelligent observer than when not so observed. Such an experimental result would not *prove* the Copenhagen interpretation, but it would tend to corroborate it because at the interpretational level the CI employs the analogous process of state vector collapse by observers. The absence of such a phenomenon does not discredit the Copenhagen interpretation, but its discovery would lend the CI considerable support. This then is what might be called a corroborative experimental result. In this section similar possible corroborative experiments for the transactional interpretation will be discussed.

What corroborative results might bear on the transactional interpretation? Experiments concerning absorber deficiency at cosmic distance scales[8], detailed studies of the character of quantum randomness[9], or searches for physical effects arising from unconfirmed TI transactions would all bear on the transactional interpretation. Further, a definitive characteristic of the transactional interpretation is that it describes causality as arising from precariously balanced cancellations that nullify the occurence of advanced effects in quantum events. We can speculate that for sufficiently small distance scales or sufficiently short time scales this balance might fail and violations of microcausality might appear. The observation of such effects would then provide corroborative support for the transactional interpretation.

It is therefore interesting to note that evidence for microcausality violations in high energy electron scattering has recently been reported by Bennett[10,11]. He has reanalyzed data from of electron-proton scattering and shown that the data exhibits a statistically significant deviation from dispersion relations based on microcausality. He proposes a semiclassical model that is ‘‘precausal’’ in that it contains acausal terms corresponding to advanced effects, and he shows that with such a model he is able to fit the experimental data.

In our opinion it is too early to base conclusions about quantum mechanical interpretation on Bennett's interesting results. Before it is concluded that microcausality has failed the data should be carefully evaluated and if possible remeasured, and other possible explanations for the observed effects should be eliminated. In particular, it should be clearly demonstrated that the reported effect does not arise from a breakdown of local commutativity having its origins in the quark structure of the proton. In any case, this area of physics should be closely watched, for its implications for the foundations of physics could be very profound.

Added Note: Prof. Steven Weinberg's investigations of the consequences of adding a small nonlinear term to the conventional quantum mechanics formalism has led to the realization that the physical effects of such nonlinearities (if they existed) could be used to experimentally distinguish between rival QM interpretations (and to demonstrate the inadequacy of the Copenhagen interpretation). The interested reader is referred to the discussion of this work in my column published in the October-1991 issue of Analog Magazine and to the references contained therein.

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